SubNet – Predicting Sources of Sediment at Sub-catchment Scale Using SedNet

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Abstract: A detailed sediment budget has been derived for Weany Creek sub-catchment (13.5 km^2) in North Queensland using SedNet. SedNet is a GIS-based software package originally developed by CSIRO for use in the Australian National Land and Water Resources Audit ("the Audit"). It was used to assess water quality in the major catchments throughout Australia. We use the term "SubNet" to refer to the application of SedNet at sub-catchment (or large paddock) scale. SedNet models estimate river sediment loads by constructing material budgets that account for the main sources and stores of sediment. At whole-of-catchment scale, such as in the Audit, SedNet input database requirements (eg. sediment contributors, channel size and condition, and water storage) were impractical to measure. The Audit relied on regionalisation to determine inputs to the model (i.e. used rules to relate mapped environmental/spatial factors to a database of measured/known values). In Weany Creek, we had detailed airphoto and DEM data (providing measurements of vegetation cover, slope, channel width) as well as extensive field measurements (for bank and gully erosion rates, stream flow and suspended sediment concentrations). The Weany Creek SubNet model has been able to show in detail which stream sections (or their associated watersheds) contribute most to suspended sediment loads (and whether it comes from hillslope, or combined gully/bank erosion, or both) as well as where bedload deposits are likely to accumulate. SubNet has provided valuable insight into the meso-scale dynamics of erosion and sediment transport processes and their impacts within the catchment as well as on downstream water quality.

Keywords: *Stream sediment; Sediment budget; SedNet; Water quality*

1 STUDY AREA

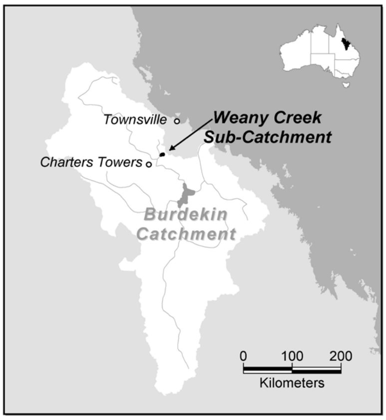

Figure 1. locality map

Weany Creek is located near Mingela in the Goldfields country surrounding Charters Towers in North Queensland. This places it within the Burdekin River Catchment, an area identified as high risk from both gully erosion and hillslope erosion (Prosser et al., 2002)

Weany Creek is currently the focus of detailed erosion and water quality monitoring by CSIRO. Plot, hillslope, and sub-catchment scale measurements are being captured using various field techniques. These measurements have provided either validation of or inputs to the SubNet model.

The climate at Weany Creek is tropical semi-arid with a mean annual rainfall of 550 mm/yr falling mostly during the summer wet season (Dec-Mar). Weany Creek is an ephemeral stream, only flowing during and after rainfall events. Gullying within the catchment is well developed and was probably initiated when grazing was introduced around the turn of last century. Cattle grazing is still the dominant landuse. Vegetation consists of open eucalypt woodlands with a grass understory.

Weany Creek drains a small catchment (13.5 km^2) of mostly Dalrymple soil overlying Granodiorite. According to Rogers et al. (1999) "Dalrymple soil is formed from granodiorite and similar granitic rock and is moderately fertile…. The soil is weak to moderately dispersive in the surface and not dispersive in the subsoil."

2 BACKGROUND

The acronym SedNet stands for the Sediment River Network Model. SedNet is a software package originally developed by CSIRO for use in the Australian National Land and Water Resources Audit ("the Audit") for use in assessing water quality in the major catchments throughout Australia. (Prosser *et al*., 2001). It is now being applied at regional scales such as river catchments, using more detailed inputs. The Weany Creek is the first attempt to use SedNet at sub-catchment (large paddock) scale.

SedNet models estimate river sediment loads by constructing material budgets that account for the main sources and stores of sediment. SedNet models use a simple conceptualisation of transport and deposition processes in streams. Sediment sources, stream loads, and areas of deposition within the system can be produced. The contribution from each watershed to the river mouth can be traced back through the system, allowing downstream impacts to be put into a continental perspective.

At the scale of the Audit, and even at most regional scales, SedNet inputs (eg. sediment contributors, channel size and condition, and water storage) are impractical to measure. Regionalisation was used to determine inputs to the model. Regionalisation uses rules to relate mapped environmental/spatial factors to a database of measured/known values. Some factors, such as riparian vegetation, were inferred using surrogates such as native vegetation mapping.

Information on SedNet model development and/or regionalisations and approximations used in the Audit are detailed in a series of CSIRO Land and Water technical papers and other related publications – Hughes, *et. al* (2001), Gallant (2001), Lu *et. al* (2001), Prosser *et. al* (2001), and Young *et. al* (2001). Application of SedNet to regional scale catchments can be found in DeRose *et. al* (2002) and Prosser *et. al* (2002).

3 DATA PREPARATION

A set of air photos were captured at 1:8000 scale for the Weany Creek sub-catchment. From these, colour digital orthophotos at 25 cm resolution and a digital elevation model (DEM) (gridded at 5m and accurate to better than 50cm in Z) were derived. Extensive field measurements and monitoring results were also available. Thus, many of the input parameters that had been estimated by regionalisation or surrogates in the Audit or in regional catchment studies, could be directly measured for Weany Creek.

3.1 Stream links and Watershed

The basic unit of a SedNet Model is a stream link. As for other SedNet studies, the stream links were generated automatically from the DEM. Topology was created for each stream link to identify its upstream and downstream relationship to other stream links and its overall position within the system (stream order). For each stream link a unique watershed was identified by a polygon area. The stream links formed the framework into which data was entered in preparation for running the SubNet model. The watersheds, as well as providing measurement of upstream catchment area for hydrological parameterisation, defined the areas within which spatially distributed erosion data needed to be summarised for each stream link.

3.2 Hydrological Setting

To run SedNet, hydrological parameters, for prediction of sediment transport and deposition within the river system, need to be estimated and attached to each stream link. In the Audit and the regional studies, channel width, mean annual flow and bankfull discharge are generally only known in only a few places, so regionalized values were created.

For Weany Creek, channel widths were measured for each stream link section directly from the air photos. Mean annual flow (defined from discharge) was measured at the outlet of the catchment and estimated for each stream link by scaling against upstream catchment area. Bankfull discharge was not required as floodplain deposition was not being modelled.

As with all other Sednet studies, connectivity, channel gradients, and stream order information were derived during stream link creation.

The small size of Weany catchment meant there were no large reservoirs or lakes, nor any significant floodplains. As these are the areas SedNet models as depositional, it meant that essentially all fine sediment input to the SubNet stream links was transported out of the catchment.

3.3 Gully and Stream Bank Erosion

3.3.1 Previous studies

In the Audit and regional studies, bank erosion was estimated from Bankfull discharge and percentage of intact riparian vegetation within each stream link. Gully erosion rates were estimated using airphoto interpretation to regionalise gully density based on topographic, geomorphic and geological information.

3.3.2 Gully Mapping

In Weany Creek, we mapped all gullies and streams using the airphotos and field observations. We then divided each gully into three distinct sections using a fixed percentage of their total length based on field observations.

Each section represented a different erosional regime. Streams were not subdivided.

Gully heads – top 23% of the gully – these are the most active part of the gully, where the most slumping occurs, and where all of the gully head advance takes place, walls are vertical or nearly so.

Gully middles – middle 38% of the gully – these still have a significant amount of slumping, although the walls tend to slope at a lower angle.

Gully valleys – bottom 39% of the gully – these behave more like a stream, and in general have less slumping than either of the categories above.

Streams – defined as those present in the 1:250 000 topographic mapping – rates of stream bank erosion are assumed to be the same as in gully valleys.

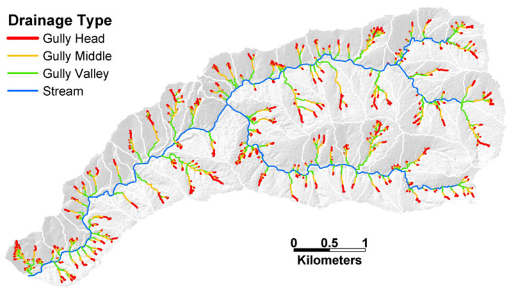

Figure 2. Detailed gully/stream mapping for Weany Creek

3.3.3 Riparian Veg Mapping

The percent of riparian vegetation was determined by estimating the percentage area covered by trees within a 5m buffer of the edge of each gully/stream. Trees were identified using the vegetation cover index (see section 3.4.5),

3.3.4 Gully and Stream Erosion Rates

In Weany Creek, we had field measurements of gully head migration and gully wall slumping (equivalent to bank erosion at this scale). Kinematic GPS was used to measure gully head migration. Erosion pin surveys monitored changes in cross-section due to side-wall slumping in the gully heads.

Based on three years worth of measurements, gully head migration was estimated to be in the order of 0.05 metres/year. A slumping rate of 0.016m^2/m was determined from the cross-sectional data. For an averaged sized gully (1.5m deep and 1m wide), this equated to about 0.17 t/yr of gully head migration per gully and 0.024 t/m/yr of slumping (bank) erosion.

Gully slumping was not measured in gully middles and valleys. We therefore assumed that slumping in middle sections occurred at 50% of the rate monitored at gully heads, while slumping in gully valleys occurred at 25% of the rate monitored at gully heads. Similarly, stream bank erosion was assumed to occur at 25% of the rate seen for gully head slumping. Work is currently underway to refine these figures based on additional monitoring sites. Total gully erosion per watershed was calculated and attached to the corresponding stream links.

3.4 Hillslope erosion

Hillslope erosion was estimated using the Universal Soil Loss Equation (USLE) where:

$$Soil\ Loss\ (t/ha/yr) = R \times K \times L \times S \times C \times P$$

R = rainfall erosivity factor
K = soil erodibility factor
L = hill length factor
S = hillslope factor
C = vegetation cover factor
P = Land Use Practice Factor (not used)

All factors were represented as spatially variable grids, allowing derivation of a spatially distributed hillslope erosion grid.

An additional term, the hillslope delivery ratio (HSDR) was also used to account for resettling of hillslope sediment before it reaches a stream. Therefore:

$$Total\ sediment\ delivered\ to\ stream = RKLSC * HSDR$$

3.4.1 Rainfall Erosivity Factor (R)

Rainfall erosivity is a measure of the intensity of rainfall events and so is determined by climatic data. For Weany Creek we used an average value based on an erosivity grid created for the Burdekin (Prosser et al., 2002) For Weany Creek the average R was 2722 MJmmha^{-1}hr^{-1}yr^{-1}.

3.4.2 Erodibility Factor (K)

Erodibility is a measure of the susceptibility of the soil to erosion. It is based on the nature (structure, texture etc) of the topsoil. The Weany Creek sub-catchment is mapped as Dalrymple Soil Association according to the Dalrymple Land Resource Survey (1:250,000). A K factor of 0.03 was estimated for this soil association and applied as a constant for the entire catchment.

3.4.3 Hill length Factor (L)

The hill length factor reflects increasing runoff volume (and thus eroding power) downslope. However, in grasslands and open woodlands the hill-length term (L) was considered invariant and was removed from the analysis (i.e. set to 1).

3.4.4 Hillslope Factor (S)

The hillslope factor accounts for the fact that soil erosion increases with increasing slope. The angle of slope was determined using a slightly smoother version of the DEM (5x5 pixel). Slope angle for each cell was determined by analysing the surrounding 3x3 matrix of grid cells. Slopes in Weany Creek sub-catchment are gentle and, although ranging from 0% – 66%, the average slope was only 4% with a standard deviation of 2.5%, resulting in a hill slope factor averaging 0.46.

3.4.5 Cover Factor (C)

Vegetation cover was classified by creating a vegetation index from the 25 cm pixel scanned colour airphotos. To obtain the vegetation index, the PD54 (Pickup *et. al.,* 1993) method was employed on a 2m pixel re-sampled photo mosaic. PD54 differentiates between vegetation cover and bare soil by comparing reflectance of red and green visible light.

We classified ground cover into 5 categories (see Figure 3). Areas of known scald were mapped as bare, trees populated the highest values of the index, then three intermediate cover classifications were identified representing the varying cover present in the open grassy areas.

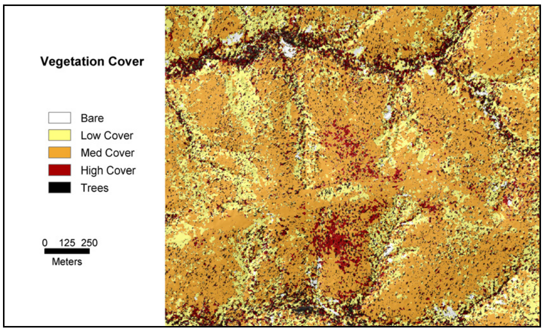

Figure 3. Vegetation Cover classes based on the PD54 greenness index

We then assigned what we considered "typical" cover factors (see Table 1) (where higher values mean more erosion) for each cover class to create a grid of C values. The C factor represents a comparison of soil loss with that expected from freshly tilled soil (C=1).

Table 1. Summary of vegetation cover categories and C factors for Weany Creek

Cover	Area of Catchment	C Factor
Trees	16%	0.01
High	16%	0.01
Medium	41%	0.1
Low	24%	0.4
Bare	3%	0.5

3.4.6 Land Use Practice Factor (P)

This accounts for the effects of contours, strip cropping or terracing. As these are not practiced in the Weany Creek sub-catchment, this factor was not used (i.e. set to 1)

3.4.7 Hillslope Delivery Ratio (HSDR)

HSDR was approximated to a constant (0.05 = 5%) for the Audit. The scale of the Audit data validated such an approximation. However at finer scales such an approach would be unrepresentative. Factors such as soiltype and vegetation cover can effect the HSDR. However, because soil was invariant at this scale and vegetation cover was similar in pattern throughout the sub-catchment, we ignored these effects and instead based HSDR on the purely spatial observation that hillslope erosion occurring close to streams or gullies is more likely to contribute to stream sediment concentrations. So for Weany Creek we modelled a spatially variable HSDR based on our current state of knowledge:

$$HSDR = 0.1366 \times e^{(-0.0091 \times \langle \text{Distance to stream} \rangle)}$$

This relationship provides agreement with the following observations:

- HSDR has an inverse exponential relationship to distance from drainage (Lu, pers. comm.);
- HSDR has reduced to 5% by around 100m from the stream;
- HSDR appears to be negligible (1% or less) after about 300m from the stream;
- The average HSDR for the catchment is 5%.

Figure 4 shows the final grid of hillslope erosion, showing the attenuation of the RKLSC grid by distance from stream/gully.

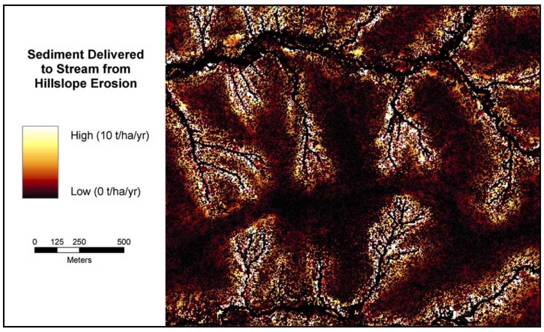

Figure 4. Hillslope erosion contributing to stream sediment based on the RKLSC grid attenuated by a spatially variable HSDR.

4 ANALYSIS OF WEANY CREEK USING SUBNET

Once all the input parameters were attached to the stream links of the model, a sediment budget was determined for each stream link. The erosion rates and outputs from upstream links told the model how much sediment was being input into each stream link and the hydrological parameters told the model how much sediment was being transported through or deposited within each stream link.

4.1 Sources of Sediment

Figures 5 and 6 show the relative contributions of sediment made by each stream link watershed.

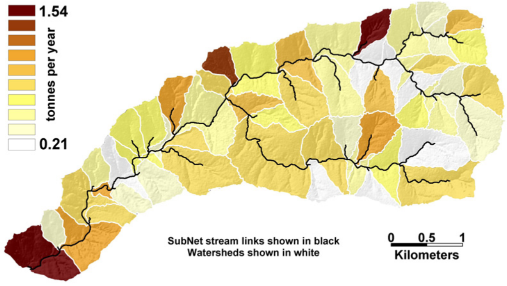

Figure 5. Gully erosion per Watershed

It can be seen by a comparison of Figures 2 and 5 that, as might be predicted, gully and bank erosion is at its highest in watershed with a more dense network of gullies and/or watersheds which have a higher proportion of gully heads and gully middles to gully valleys and streams.

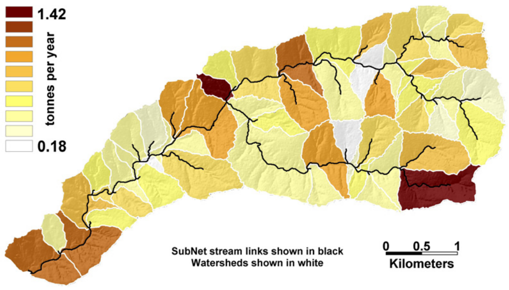

Figure 6. Hillslope erosion per Watershed

Relative contributions to hillslope erosion made by each stream link watershed are shown in Figure 6. Higher erosion rates can be attributed to either to lack of vegetation cover and/or steeper slopes.

4.2 Fate of Sediment

SedNet has two sediment transport routines - one for fine sediment and one for coarse.

Based on the soil type in this region, we have assumed a 50:50 split between fine and coarse fractions in the sub-soil. All sediment eroded from gullies, regardless of size fraction, is added directly into the stream. For Hillslope erosion, the combined USLE-HSDR erosion rate assumes that only fine sediment is eroded and transported overland to gullies and streams. Thus, hillslope erosion rates report only the fine fraction. Since the Weany Creek sub-catchment does not have any floodplains, dams or lakes, the model will invariably transport all this fine sediment out of the system.

Coarse sediment may or may not stay entrained depending on the stream transport capacity calculated for each stream link using flow variables. If it cannot remain entrained, a depositional rate is calculated for the affected stream link. Table 2 summarises the sediment budget for Weany creek derived from SubNet.

Table 2. Sediment budget estimated by the Weany Creek SubNet model

Budget Component	Coarse Bedload (tonnes/year)	Fine suspended sediments (tonnes/year)	Total sediments (tonnes/year)
Hillslope delivery	0	432	432
Gully erosion :			
- *Head advance*	*(66)*	*(66)*	
- slumping - *heads*	*(153)*	*(153)*	
- *Slumping - middles*	*(104)*	*(104)*	
- *Slumping - valleys*	*(47)*	*(47)*	
Total gully erosion	370	370	740
Streambank erosion	28	28	56
Sediment delivered To streams	**398**	**830**	**1228**
Sediment stored in streambed	**354**	**0**	**354**
Sediment exported	**44**	**830**	**874**

5 DISCUSSION

Table 2 indicates that the stream power of Weany Creek is not sufficient to export all of the coarse sediment from the catchment. As a result 89% is stored within the catchment, with the other 11% exported. This represents an accumulation of less than 1 cm of sand per year in the 21 km of streams in the catchment, and is thus entirely reasonable.

We were able to ground-truth the model prediction of fine sediment export by comparing the prediction with our measurements of fine sediment export from the Weany Creek sub-catchment derived from a stream gauging station located at the outlet. The total suspended sediment measured at the gauge site is shown in Table 3.

Table 3. Fine sediment exported from Weany Creek Sub-catchment based on stream gauge measurements.

Season	Total Suspended Sediment
1999/2000	803 tonnes
2000/2001	399 tonnes
2001/2002	435 tonnes
Average	**546 tonnes**

Given that the 2000/2001 and 2001/2002 wet seasons were below average rainfall, this average compares favourably to the 830 tonnes per year predicted by the SubNet model. There is no field data yet to allow apportioning of the exported suspended sediment to particular sources. SubNet predicts approximately equal amounts deriving from gully erosion and hillslope erosion.

6 CONCLUSION

The detailed spatial representation of hillslope erosion and the unique methodologies for deriving gully and streambank erosion employed for SubNet has given us a unique opportunity to gain insight into the sensitivity of a stream system to the effects of landscape processes. We were able to identify the relative importance of hillslope vs. gully or bank erosion at a sub-catchment scale. This is the advantage of SubNet and will form the basis for further work at this scale.

By assisting us to trace potential sources of suspended sediments (and therefore nutrients and possibly contaminants) to specific locations within a sub-catchment/paddock (rather than just to the sub-catchment itself), as well as providing information about the major contributor type (i.e. bank/gully or hillslope erosion processes), SubNet provides an ideal tool for targeting catchment remediation action. These actions may include riparian fencing, ripping of gullies, revegetation, or exclusion of cattle.

The SedNet backbone of SubNet allows for calibration of models to any climatic, geological, or topographical regime. Thus the SubNet modelling approach can be applied to other catchments with different landuse, soils, climates, etc., or at differing scales. It should prove to be a useful tool in assessing the sources of suspended sediment in a variety of catchments worldwide.

7 ACKNOWLEDGMENTS

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